Dusty, Radiation Pressure Dominated Photoionization: The Solution to the Narrow Line Region Problem

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Abstract. Seyfert narrow line regions (NLR) have emission line ratios which are remarkably uniform, displaying only ∼0.5 dex variation between different galaxies. Existing models have been unable to explain these observations without the introduction of ad hoc assumptions, geometrical restrictions or new parameters. Here we introduce a new model: dusty radiation pressure dominated photoionization, which provides a natural self-regulating characteristic leading to an invariance of the spectrum over a very wide range (> 100) of ionization parameter. The dusty model is able to reproduce both the range and the absolute value of the observational line ratios not only in the standard optical diagnostic diagrams but also in UV diagnostic plots, providing an explanation to the problem in NLR observations.

1. Introduction

The emission lines of active galaxies have often been used in conjunction with models to constrain the physical and ionizati on structure of the emitting regions. In particular ratio diagrams or line diagnostic diagrams prove to be an excellent visual aid in interpreting the emission line data. For example, the line diagnostic diagrams by Veilleux & Osterbrock(1987) are capable of distinguishing three different groups of emission line galaxies: those excited by starbursts and two excited by an active nucleus - the Seyfert narrow line regions (NLRs) and the low ionization nuclear emission-line regions (LINERs). These diagrams are additionally interesting in that they show that the emission from Narrow Line Regions (NLR) is remarkably uniform, with only ∼0.5 dex variation between Seyferts and less within individual galaxies. This uniformity of the spectral properties has since been confirmed in much larger samples (eg. Véron-Cetty & Véron(2000)).

The standard paradigm proposes that the NLR are excited by photons originating at or near a compact nuclear source (see, eg. Osterbrock(1989)) having a smooth featureless power-law, or broken power-law EUV ionizing spectrum. Within this model, the clustering of the observed line ratios within such a restricted domain of parameter space presents a problem, as it requires an approximately constant ionization parameter† of $U \sim 10^{-2}$, whereas U should be free to take on any value. Modellers have been therefore forced to make the arbitrary (and possibly unphysical) assumption that the gas density in the ionized clouds must fall exactly as the inverse square of the distance from the nucleus.

In order to account for this failings of the previous standard models we have proposed a new paradigm for the photoionization of the NLR clouds, that of dusty, radiation pressure dominated photoionization (Dopita et al.(2002)).

† The ionization parameter is a measure of the number of ionizing photons against the hydrogen density ($U = S_\star/\mathrm{n_H}c$).

2. A New Paradigm

The inclusion of dust into photoionization models affects the final emission spectrum in several ways. As well as simply absorbing EUV radiation and competing with Hydrogen for the ionizing photons, dust affects the temperature structure of the NLR clouds through the process of photoelectric heating.

In order to be physical, an isobaric photoionization model must include the effects of radiation pressure. The force of radiation can be imparted to both the gaseous medium and dust, and results in a radiation pressure gradient. Since in photoionized nebulae dust grains are charged and therefore locked to the plasma by coulomb forces, the radiation pressure gradient on dust results in a gas pressure gradient. Standard photoionization models are isochoric and therefore cannot take this effect into account. To demonstrate these effects we have run the standard isochoric model and the new dusty, radiation pressure dominated model over a large set of input parameters.

With simple calculations it is easy to show that at an ionization parameter of $\log U \sim -2$, dust begins to dominate the opacity of the ionized cloud and hence the radiation pressure (Groves, Dopita & Sutherland(2004a)). It is also around this value of the ionization parameter that radiation pressure developed at the ionization front of the NLR cloud becomes comparable with the gas pressure. Therefore at high ionization parameters, the pressure in the ionized gas, and hence density, is determined by the external ionization parameter, U_0 and the local ionization parameter becomes independent of the external ionizing flux. The result of this is that at high ionization parameter the emission line spectrum of the low- and intermediate ionization species is effectively independent of the external ionization parameter.

3. Resulting Line Diagnostic Diagrams

The success of the dusty models in reproducing a small range in standard emission line ratios over a large range in U_0 is clearly demonstrated in the standard line diagnostic diagrams shown in figure 1 (Groves, Dopita & Sutherland(2004b)). Figure 1a, b & c show the diagrams suggested by Veilleux & Osterbrock(1987) of [N II]$\lambda6583$/Hα, [O I]$\lambda6300$/Hα, and [S II]$\lambda\lambda6717, 30$/Hα versus [O III]$\lambda5007$/Hβ respectively. In each case the dust-free curves are able to reproduce the observations, yet are unable to properly constrain the data without assuming constant U_0. The dusty models however are able to not only reproduce the data but also "stagnates" at high U_0 in the region occupied by the observations.

Figure 1d shows the He II$\lambda4686$/Hβ vs. [O III]$\lambda5007$/Hβ diagram which differs from the previous three as the He II/Hβ ratio shows greater spread than the standard model. This demonstrates another success of the dusty models as they are able in this diagram to reproduce the spread in He II/Hβ and the restricted range of [O III]/Hβ in this diagram. Here it is the hardening of the spectrum by dust and the determination of the density in the low-ionization region by radiation pressure which combine to create this spread in He II.

The dusty model is not only able to reproduce the observed values and clustering of emission line ratios in the visible it is also able to do so at ultraviolet wavelengths as well. Figure 2 demonstrates this with two UV line ratio diagnostic diagrams. The first, figure 2a, shows C IV $\lambda1549$/C III]$\lambda1909$ against C IV $\lambda1549$/He II$\lambda1640$, and reveals again the success of the dusty models in not only attain similar values to that observed in Seyfert galaxies, but in providing a mechanism for the observed clustering on the diagram. The second figure, showing [Ne III]$\lambda3869$/[Ne V]$\lambda3426$ against C III]$\lambda1909$/C II]$\lambda2326$, is
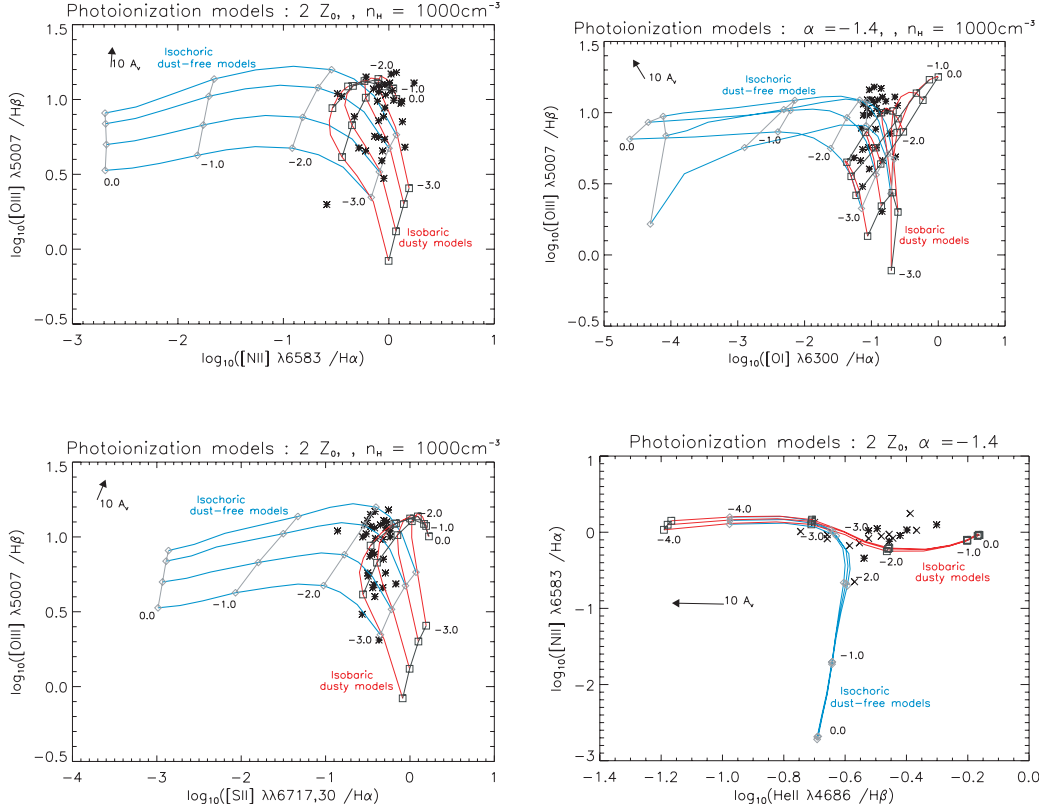
Figure 1. Four visible line diagnostic diagrams demonstrating the difference between a standard, dust-free photoionization model (light diamonds) and our dusty, radiation pressure dominated model (dark squares) in reproducing observations of seyfert galaxies (asterisks). On each figure the effects of 10 magnitudes of visual extinction due to dust are marked. Lines of constant ionization parameter are labelled with the value of $\log U_0$.

an excellent diagnostic for shock excitation, and has been used as such for high-z radio galaxies (Inskip et al.(2002)). For those radio galaxies which are believed to be photoionized (high C III]/C II]) the dusty models can reproduce the observed values, unlike the dust-free models, and the clustering at high U_0.

One detail stands out in all these diagnostics; the dusty, radiation pressure dominated models provide undeniably the better fit to the observations over the standard dust-free models. In all cases the dusty models not only reproduce the data well, but also tend to become degenerate in terms of the ionization parameter precisely in the region occupied by the observations.

4. Conclusion

First introduced in Dopita et al.(2002), the dusty, radiation pressure dominated photoionization model, through the stagnation of the ionization parameter at large values, provides a simple explanation for the small variation of observed Seyfert NLR ratios. This stagnation is due to the effects of dust opacity and radiation pressure upon dust and is characteristic to these models. The significant point is that the dusty model is able to do this over both optical and UV ratios, without depending upon large variations in other parameters such as density or metallicity. These results not only provide an explanation
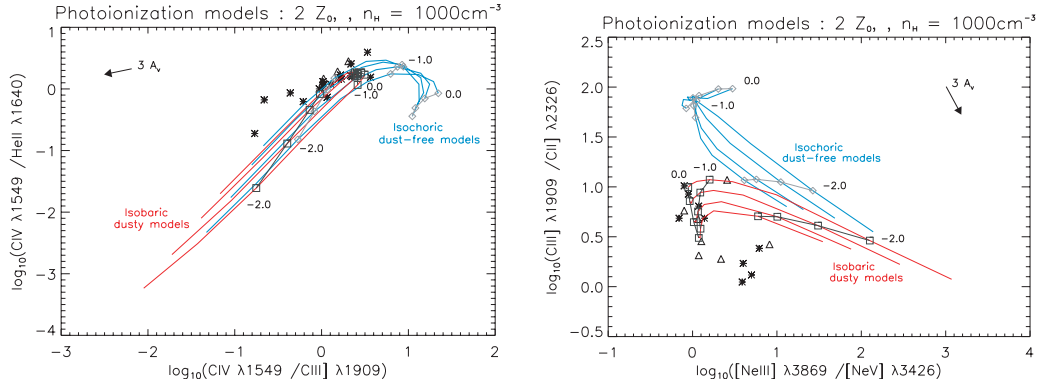
Figure 2. UV diagnostics demonstrating the success of the dusty radiation pressure dominated models in reproducing the observations compared to the standard dust-free photoionization models. Symbols are the same as in figure 1, except for the second figure where the observations are from high-z radio galaxies.

for what has not been a fully understood observation for years but also provide ways in which to understand further the processes involved in the NLR and extended NLR of AGN.

Acknowledgements

References

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